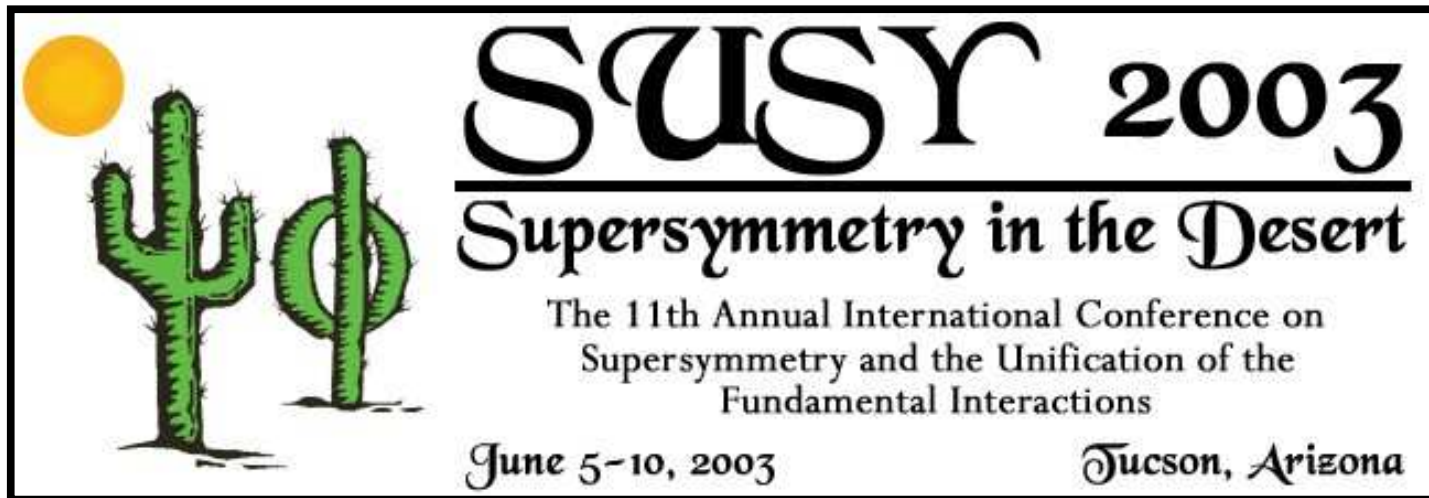


SUSY Searches with Photons in CDF



Sung-Won Lee

CDF Collaboration/Texas A&M Univ.



Sungwon Lee

SUSY 2003, Arizona



1

Outline

- **Physics Motivations ; Why Photon in SUSY...**
SUSY and New physics with photon final states
- **Measurement of Photons in CDF II**
- **New Particle Search Strategies at CDF II**
- **CDF Exotics Searches with Photons in Run II**
- **Conclusions and Outlook**

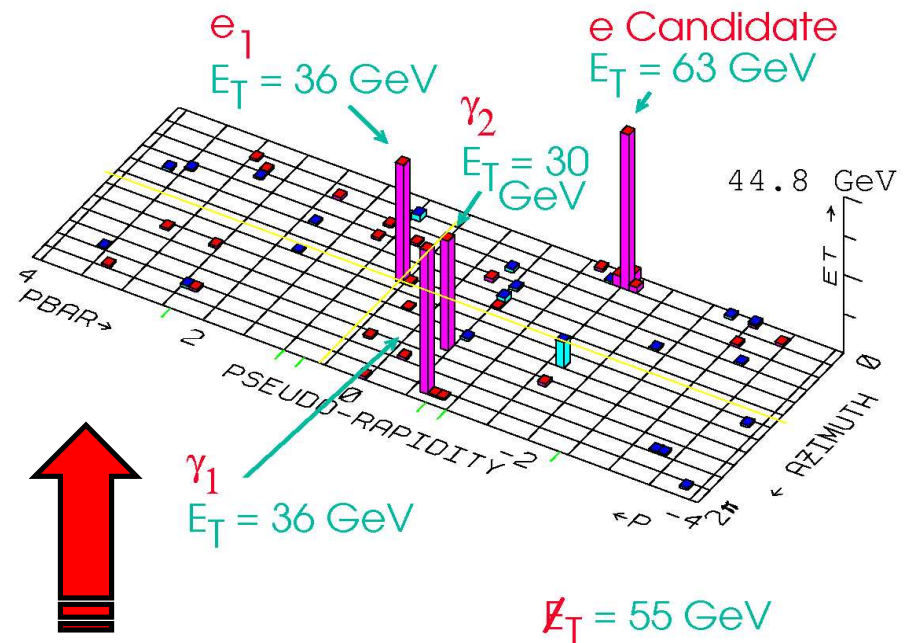


The Interesting Event on the Tail

Prologue

- On April 28, 1995, CDF recorded a spectacular $ee\gamma\gamma + \cancel{E}_T$ candidate event.
- It is unusual because isolate leptons/photons, and especially large \cancel{E}_T are rare in the Standard Model.
- Total “*a posteriori*” expected rate is 10^{-6} , including possibly misidentified particles.
- CDF recently reported an excess of events in $\mu\gamma + \cancel{E}_T$ channel that disagree with SM prediction (~ 2.7 standard deviation for Gaussian distribution)

$ee\gamma\gamma\cancel{E}_T$ Candidate Event



What is it?, Statistical fluctuation?
or Hints of New Physics?

Lots of discussion between theoretical and experimental communities
→ many theoretical interpretations...



More Interesting Event on the Tail

- CDF has performed a model independent search in Run I for new physics that gives leptons, photons, missing E_T in final state
- Inspired by $ee\gamma\gamma + \cancel{E}_T$ candidate event

The SM prediction yields the observed rate of a lepton+photon (+Missing E_T) with 0.7% probability (~ 2.7 standard deviation for Gaussian distribution)

- Search Selection:
 $l(e/\mu)\gamma$ events ($E_T > 25$ GeV)
- Main backgrounds:
W/Z+ γ , lepton+fake γ

Category	Predicted μ_{SM}	Observed N_0	$P(N > N_0 \mu_{SM})\%$
All l, γ, X	—	77	—
Z - like e, γ	—	17	—
Two - Body l, γ, X	24.9 ± 2.4	33	9.3
Multi - Body l, γ, X	20.2 ± 1.7	27	10.0
Multi - Body l, l, γ, X	5.8 ± 0.6	5	61.0
Multi - Body l, γ, γ, X	0.02 ± 0.02	1	1.5
Multi - Body l, γ, MET, X	7.6 ± 0.7	16	0.7

It's an interesting result, but it's not a compelling observation of new physics!!
Run II analysis is in progress now

Recent theoretical explanation of the $\mu\gamma$ events is...
"Resonant smuon production with a single dominant R-parity violating coupling" (hep-ph/0111014)



Photon Signatures of New Physics

- ◆ We can search for new physics with photons in the final state
- ◆ Why photon?

Empirically
interesting !!

The primary motivation for searching in photon final states is that the photon is likely to be a good probe of new interactions, particularly SUSY.

High P_T physics with photons and \cancel{E}_T

- SUSY ($N_2 \rightarrow \gamma N_1$, Light Gravitinos)
- Large Extra Dimensions
- Composite Models (Excited Leptons)
- Technicolour
- Bosephilic Higgs: $W/Z + \text{Higgs} \rightarrow W/Z + \gamma\gamma$
- Anomalous $W(\rightarrow \ell\nu)/Z(\rightarrow \ell\ell, \nu\nu) + \gamma$ production

SUSY Models

- Minimal SUSY extension of SM (**MSSM**)
- Minimal Super-Gravity (**mSUGRA**)
- Gauge Mediated SUSY Breaking (**GMSB**)



SUSY Photon Signatures at Tevatron

In recent SUSY models, two main choices of SUSY breaking have come into favor that predict photons in the final state. SUSY particles are not degenerate with Standard Model particles \rightarrow SUSY is broken either...

via Standard Model
Gauge Interactions

via Gravity
(Heavy Gravitino)

GMSB

Gravitino mass, M_G , related to
SUSY breaking scale, \sqrt{F}

LSP = Gravitino
NLSP = Neutralino

$$\tilde{\chi}^0 \rightarrow \gamma + \tilde{G}$$

Relevant mass range:
 $O(10^{-2} < M_G < 10^4) \text{ eV}$

Supergravity

Breaking transmitted to visible
particles by gravitino interaction

LSP = 1st lightest Neutralino
NLSP = 2nd lightest Neutralino

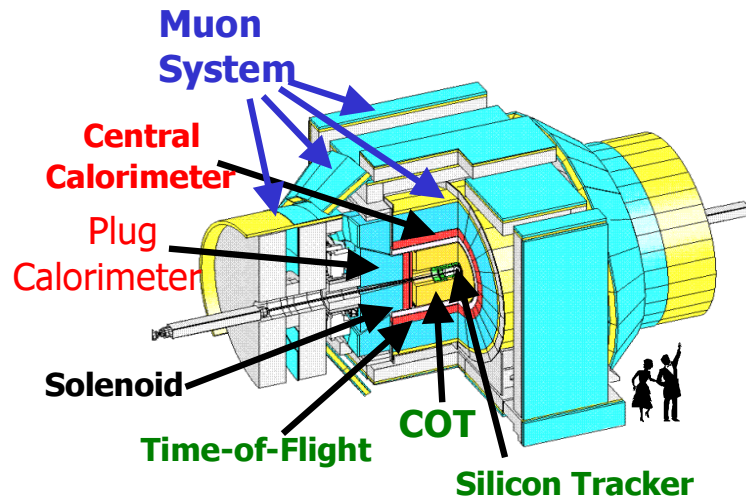
$$\tilde{\chi}_2^0 \rightarrow \gamma + \tilde{\chi}_1^0$$

If $\tilde{\chi}_1^0$ is mostly higgsino and $\tilde{\chi}_2^0$ is
mostly gaugino

The process will result in $\gamma\gamma + \cancel{E}_T + X$ events if both neutralino
decay inside the detector.



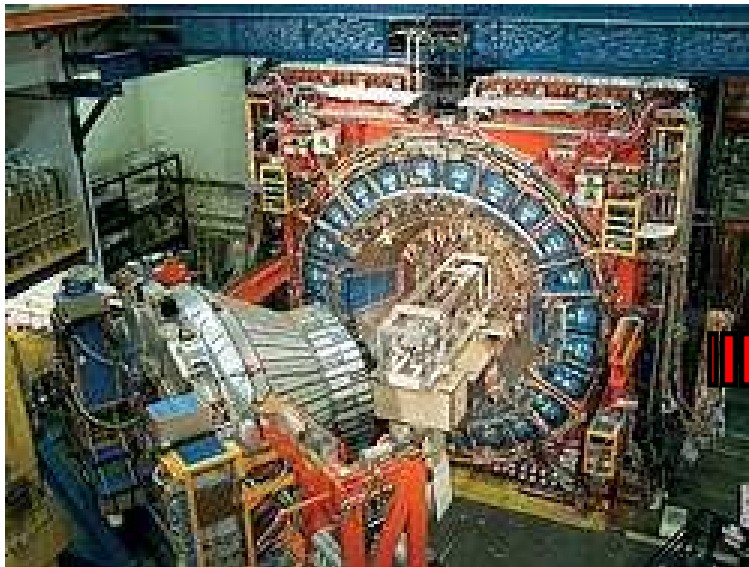
CDF II Detector @ Tevatron



CDF II detector is essentially new, commissioned and now taking physics-quality data @ 1.96 TeV since Feb 2002

Highlights of Upgrade

- ✓ New front-end, DAQ and trigger
- ✓ New silicon vertex detector
- ✓ New central outer tracker
- ✓ New end-plug calorimeters
- ✓ Extended muon coverage
- ✓ New time-of-flight system
- ✓ EM calorimeter timing (Summer 03)



Major components used in CDF II Photon Physics

1. Central EM Calorimeter System
2. Central Tracker
3. Timing from Hadron Calorimeter



Measurement of Photons in CDF II

Triggers/Dataset

Many Triggers: all are running, including L2 (central/plug photons)

- Inclusive Photon: $E_t > 25$, w/ ISO
- Ultra(Super) Photon: $E_t > 50(70)$
- Diphoton: $E_t > 12$, w/ ISO
- Diphoton: $E_t > 18$, w/o ISO
- Triphoton: $E_t > 10$, w/o ISO
- Photon: $E_t > 16$ + Muon
- Photon: $E_t > 16$ + 2 jets ($W/Z + \gamma$)
- Photon: $E_t > 10$ + SVT track

Large samples are being collected, tested and many studies started:

Backgrounds, calibration, fake rates, simulation...

Standard Photon ID

Central Photon Cuts:

- Adjust transverse quantities to vertex
- Number of 3-D track
- E fraction b/w HAD and EM Cal.
- Calorimeter Isolation
- Track Isolation
- Two topological shower quantities
 1. EM Shower width
 2. EM Shower cluster energy

Additional Selections:

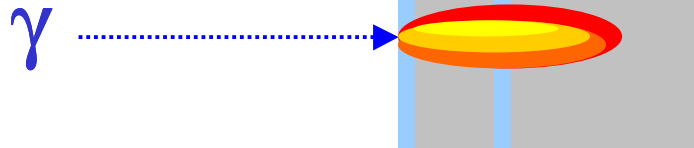
- reject cosmic-ray
- reject Tevatron Beam-Halo events



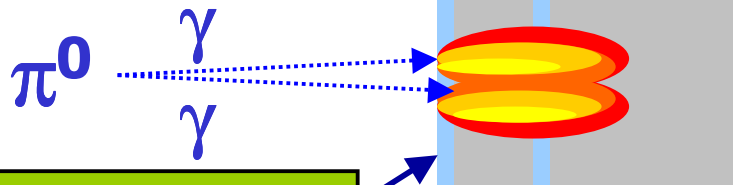
Identification of Photon Signals in CDF

Photon candidates: Isolated electromagnetic showers in the calorimeter, with no charged tracks pointing at the calorimeter cluster

• Signals



• Backgrounds



Pre-shower Detector

Shower Maximum Detector

- CDF uses two techniques for determination of photon signals;
 1. EM Shower width (shape):
using Shower Max. Detector
 2. Conversion Probability:
using pre-radiator hits
- For every photon, CDF find the fraction of candidates with these informations:
(extracted signals statistically)

e.g. for diphoton candidates,
S/B result using CPR method is..

	$\gamma\text{-}\gamma$	$\gamma\text{-Jet}$	Jet-jet
CPR	$29 \pm 23\%$	$40 \pm 28\%$	$30 \pm 23\%$

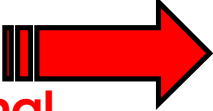


New Particle Search Strategies at CDF II

Two different approaches for new particle search with photons will be actively pursued in CDF Run II experiment in a complementary way:

✓ 1. Traditional Model-driven Analyses


- pick a favorite theoretical model & process, choose the best signature(s): optimize selection acceptance based on signal MC
- calculate the expected backgrounds
- evaluate the limit or discover a new signal



Best optimization, but model might become some outdated..

✓ 2. Signature-based Approach

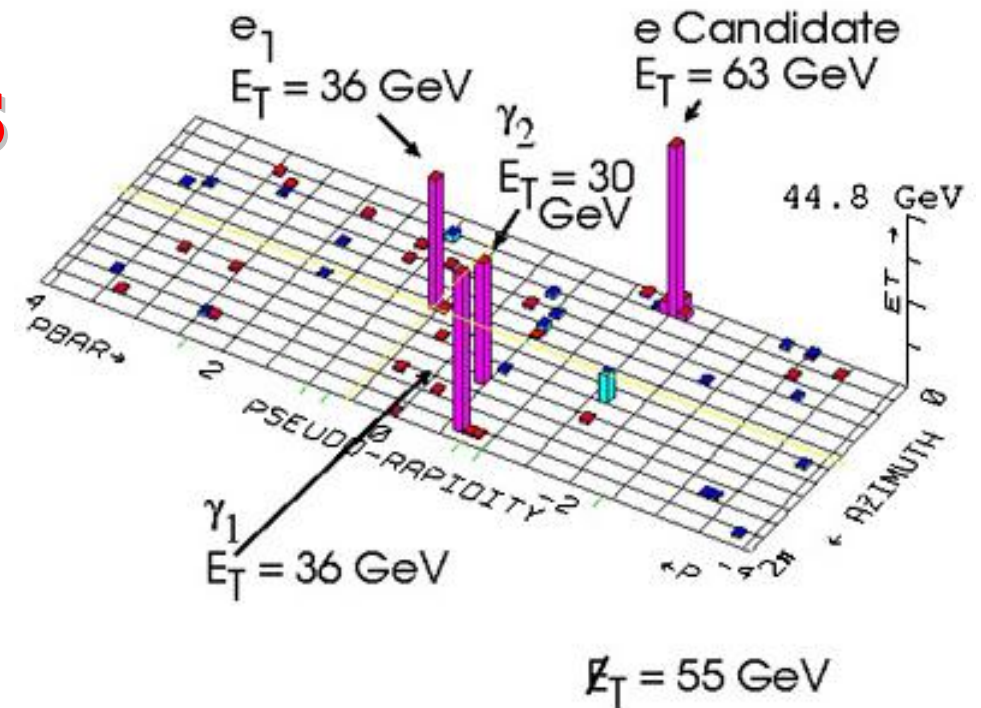
- pick a specific signature (e.g. diphoton+X)
- define the sample in terms of known processes
- publish estimates of acceptances & cross section information useful for theorists
- see an excess? inconsistency with SM? test one or more models later.



Not best optimization but open to a whole lots of models; An unbiased study is fundamental for data understanding.



Exotics Searches with Photons in CDF Run II



- Search for Anomalous Di-Photon+ \cancel{E}_T Production
- Search for Anomalous Photon+Lepton Production
- Search for GMSB with Di-Photon+ \cancel{E}_T
- Search for LED with Photon+ \cancel{E}_T
- Search for Excited Lepton with ee +photon
- Search for W/Z+Photon



$\gamma\gamma+X$ Signature-based Searches

- ◆ Run I Search for an excess of events in the $\gamma\gamma+X$ final state,
- ◆ will generalize the Cousin Search to a full Signature Based Search

where X is...

- **Gauge Boson:**
W, Z, gluon(\rightarrow jet) or extra photon
- **Quark:**
Light quarks, b-quarks, t-quarks ($t \rightarrow Wb$)
- **Leptons:**
Electrons, Muons, Taus,
Neutrinos (Missing E_T signature)
Leptons from $W \rightarrow \ell\nu$,
 $Z \rightarrow \ell\ell$, $Z \rightarrow \nu\nu$

$E_T^\gamma > 12$ GeV Threshold		
Signature (Object)	Obs.	Expected
$\cancel{E}_T > 35$ GeV, $ \Delta\phi_{\cancel{E}_T\text{-jet}} > 10^\circ$	1	0.5 ± 0.1
$N_{\text{jet}} \geq 4$, $E_T^{\text{jet}} > 10$ GeV, $ \eta^{\text{jet}} < 2.0$	2	1.6 ± 0.4
Central e or μ , $E_T^{e \text{ or } \mu} > 25$ GeV	3	0.3 ± 0.1
Central τ , $E_T^\tau > 25$ GeV	1	0.2 ± 0.1
b -tag, $E_T^b > 25$ GeV	2	1.3 ± 0.7
Central γ , $E_T^{\gamma 3} > 25$ GeV	0	0.1 ± 0.1

$E_T^\gamma > 25$ GeV Threshold		
Object	Obs.	Exp.
$\cancel{E}_T > 25$ GeV, $ \Delta\phi_{\cancel{E}_T\text{-jet}} > 10^\circ$	2	0.5 ± 0.1
$N_{\text{jet}} \geq 3$, $E_T^{\text{jet}} > 10$ GeV, $ \eta^{\text{jet}} < 2.0$	0	1.7 ± 1.5
Central e or μ , $E_T^{e \text{ or } \mu} > 25$ GeV	1	0.1 ± 0.1
Central τ , $E_T^\tau > 25$ GeV	0	0.03 ± 0.03
b -tag, $E_T^b > 25$ GeV	0	0.1 ± 0.1
Central γ , $E_T^{\gamma 3} > 25$ GeV	0	0.01 ± 0.01

Number of observed and expected $\gamma\gamma$ events with additional objects in 85 pb^{-1}

All results are consistent with the Standard Model background expectations with one possible exception, $ee\gamma\gamma + \cancel{E}_T$ event



Search for Anomalous $\gamma\gamma$ Events at CDF

- Search Selection:**

2 central photons with $E_T > 13(25)$
Cosmic and beam halo clean-up

- Main backgrounds:**

fakes from photon-jet and jet-jet

- Results:** 1365(95) events for $E_T > 13(25)$

For $M_{\gamma\gamma} > 150$ GeV
Expected background: 3.3
Observed: 2.0

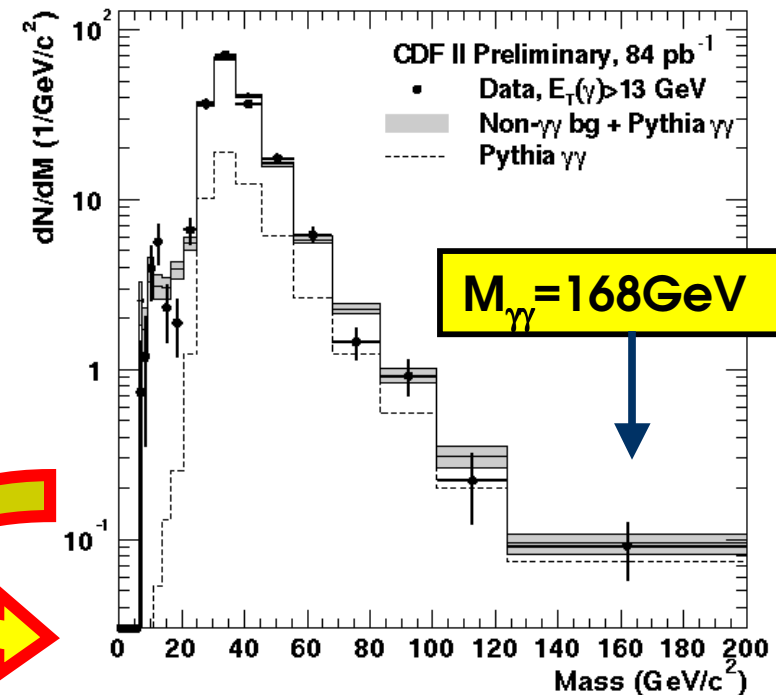
Run I Results (LED Search)

observed: 287(192) CC(CP) events

For $M_{\gamma\gamma} > 150$ GeV
Expected background: 4.5 ± 0.6
Observed: 5

95% C.L. Limits on eff. string scale:
using a maximum likelihood fit method

Diphoton Mass



NO excess observed @ High invariant mass, good agreement b/w Run II Data and expectation

95 % C.L. $M_s > 899 / 815$ GeV
 $K_{\text{LED}} = 1.0$ ($\lambda = -1/+1$, Hewett)

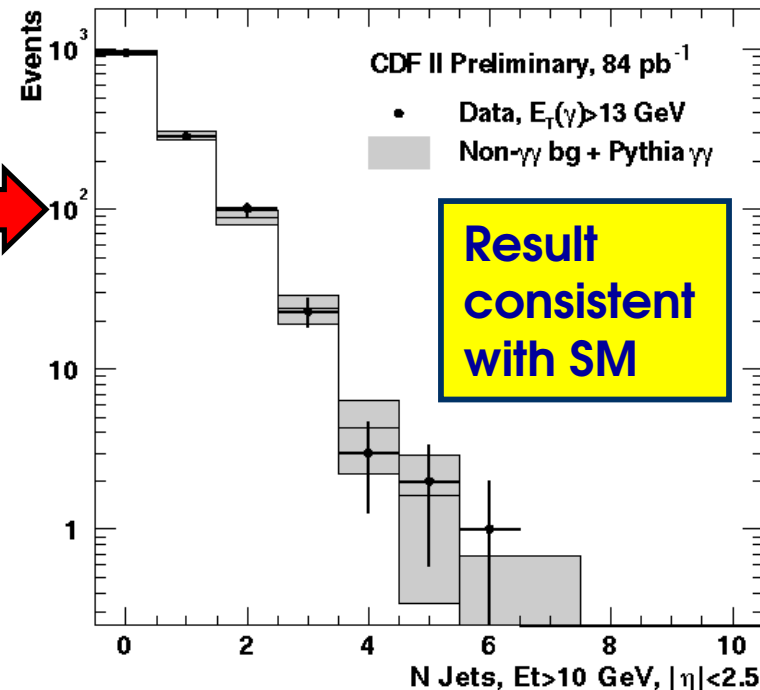


$\gamma\gamma$ +Jets, $\gamma\gamma$ +Leptons Search at CDF

- Search for $\gamma\gamma + X$; $X=\text{jet}(s)$**

To search for anomalous production of quarks and gluons, look in anomalous N_{jet} production in $\gamma\gamma$ data

N Jets in Diphoton Events



- Search for $\gamma\gamma + X$; $X=\text{lepton}(s)$**

- Search Selection:**

Diphoton+extra lepton(s) $P(\text{e fake } \gamma) = 1\%$

- Main backgrounds:**

$W/Z+\gamma\gamma$, fake γ , $Z\gamma, e(\mu)\gamma+\text{jet}$

No event is found

CDF II Preliminary $\gamma\gamma\ell$ Search, 84 pb⁻¹

Selection	Observed	Predicted
$\gamma\gamma (E_t > 13 \text{ GeV}), e^\pm (E_t > 20 \text{ GeV})$	0	$0.27 \pm 0.10 \pm 0.14$
$\gamma\gamma (E_t > 25 \text{ GeV}), e^\pm (E_t > 20 \text{ GeV})$	0	$0.04 \pm 0.03 \pm 0.02$
$\gamma\gamma (E_t > 13 \text{ GeV}), \mu^\pm (P_t > 20 \text{ GeV})$	0	$0.04 \pm 0.007 \pm 0.02$
$\gamma\gamma (E_t > 25 \text{ GeV}), \mu^\pm (P_t > 20 \text{ GeV})$	0	$0.007 \pm 0.005 \pm 0.004$

Good agreement b/w Run II data and expectation..



Search GMSB for $\gamma\gamma + \cancel{E}_T$ (I)

$$(p\bar{p} \rightarrow \chi\chi \rightarrow N_1 N_1 + X \rightarrow \gamma\gamma GG + X)$$

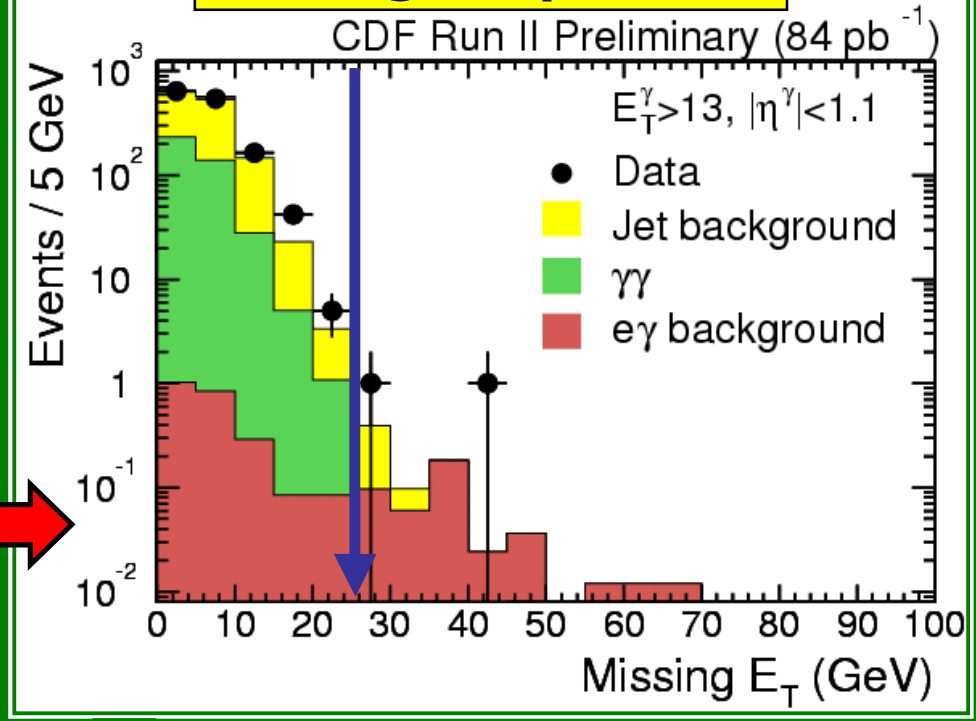
Limit on GMSB Model

- Gravitino: the LSP particle
- NLSP: Neutralino $N_1 \rightarrow \gamma G$
- **Experimental Signature: $\gamma\gamma + \text{Met}$**

SUSY would show up as an excess of events with large Missing Energy

- Search Selection:
2 central photons w/ $E_T > 13(25)$
Cosmic/beam halo clean-up
- Main backgrounds: (see plot)
QCD diphoton,
jet mis-ID, W+photon (lost track)
- Results:
1392(97) events for $E_T > 13(25)$

Missing Et Spectrum



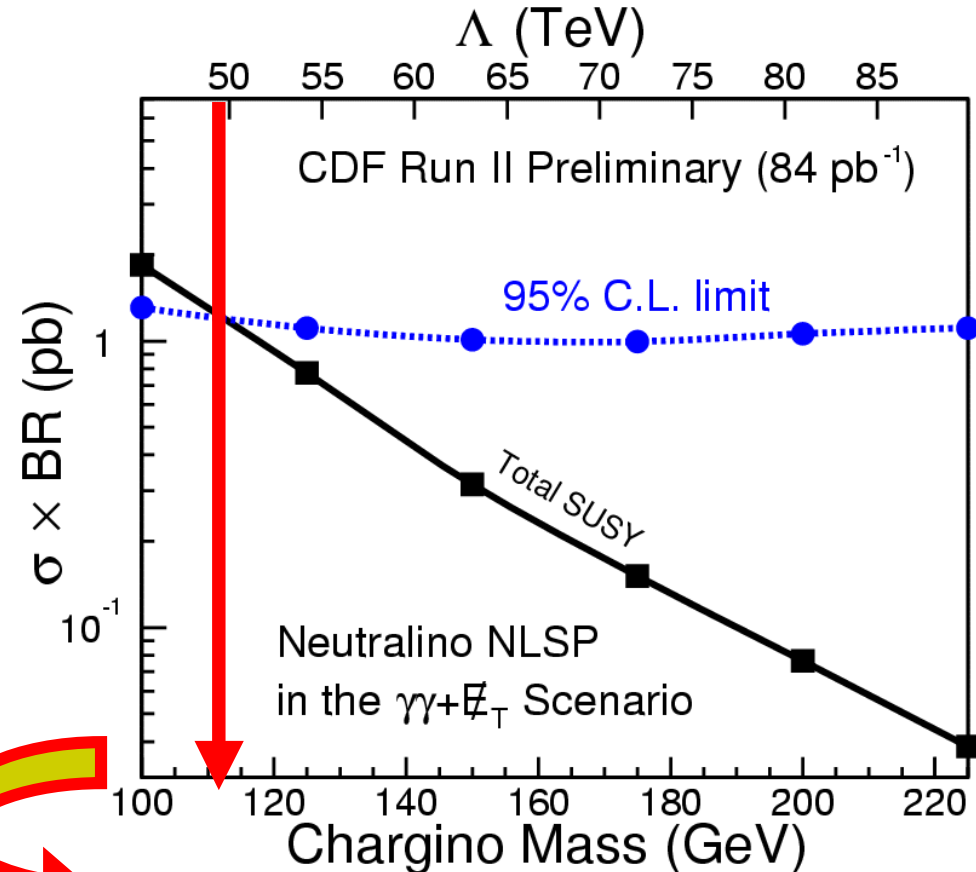
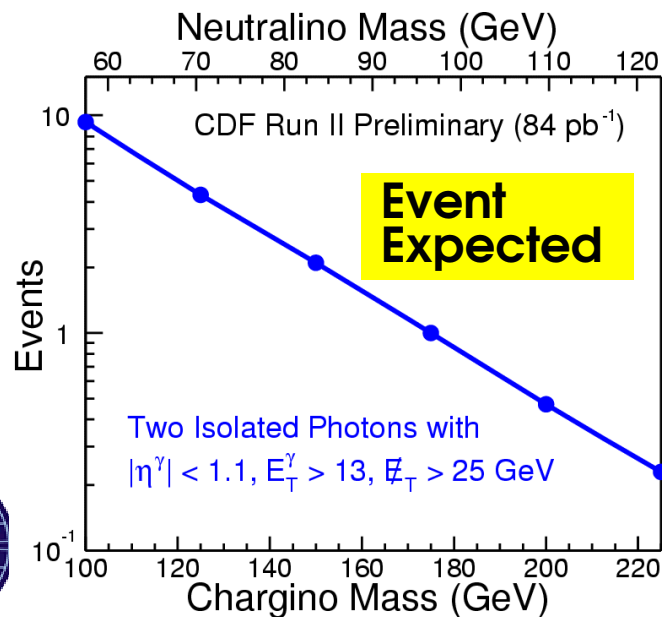
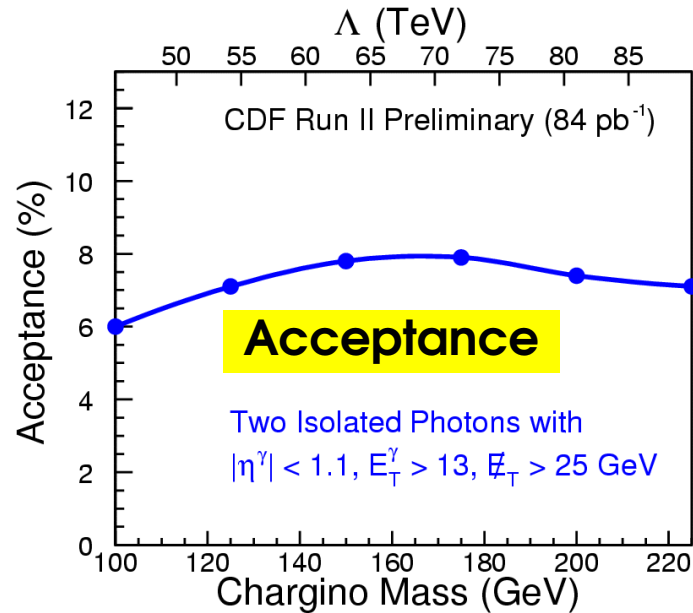
For Missing $E_T > 25 \text{ GeV}$

Expected background: **2+2**
 Observed: **2**

→ **Set cross section limit, now**



Search GMSB for $\gamma\gamma + \cancel{E}_T$ (II)



Search for New Physics in $\gamma + \cancel{E}_T$

Search Selection: (84 pb⁻¹)

- one γ with $E_T > 47$ GeV and $|\eta| < 1$
- Missing $E_T > 42$ GeV
- No jets with $E_T > 10$ GeV
- No tracks with $p_T > 5$ GeV

Main backgrounds:

Cosmic ray muons	3.9 ± 1.0
$Z\gamma \rightarrow \nu\nu + \gamma$	4.8 ± 0.5
$W \rightarrow e\bar{\nu}$	7.3 ± 1.7
QCD diphotons	1.1 ± 0.4
$W\gamma$ ($\nu\gamma$)	0.9 ± 0.3

Results: No excess was found

Expected background: 18.0 ± 2.1

Observed: 17

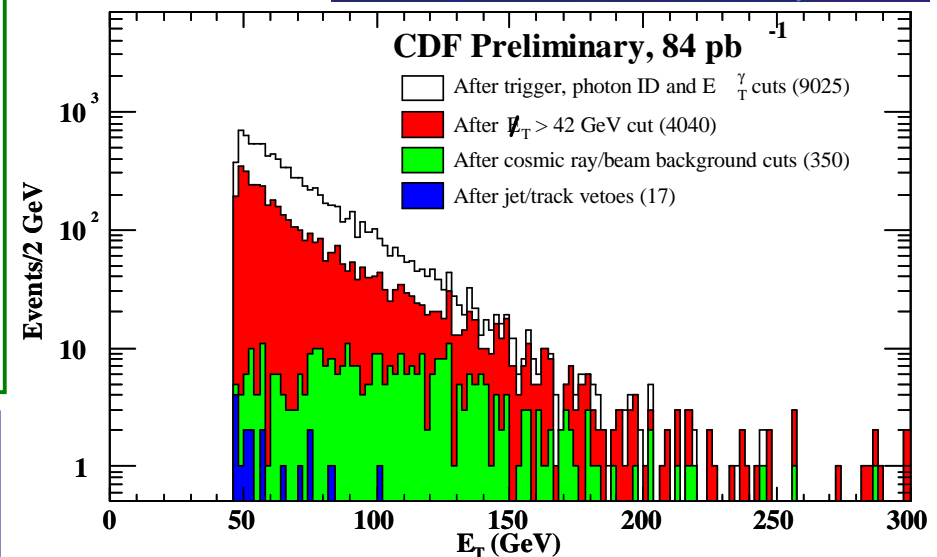
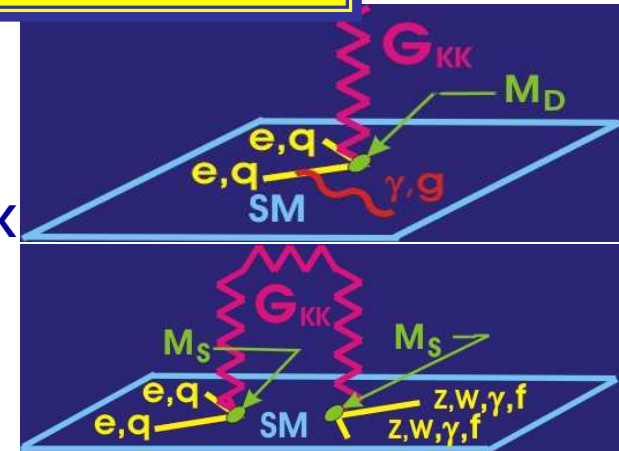
95% C.L. upper limit on
(accep. x eff. x cross-section) of
121 fb was set: (2.1 x expected
 $Z\gamma$ signal)

Extra Dimensions

ADD

$q\bar{q} \rightarrow \gamma G_{KK}$

Randall-Sundrum



Limit on New Physics



Sungwon Lee

SUSY 2003, Arizona

17

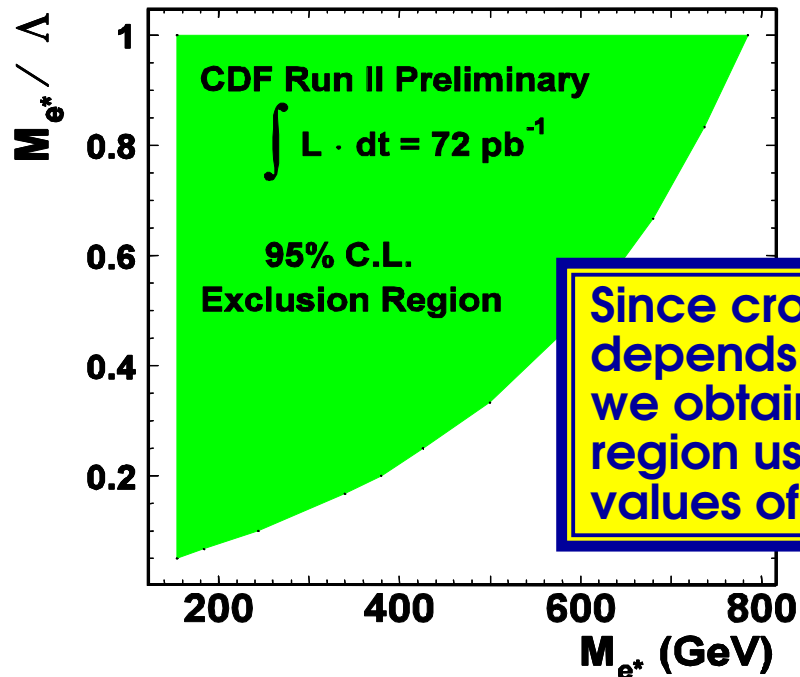


Search for Excited Electrons

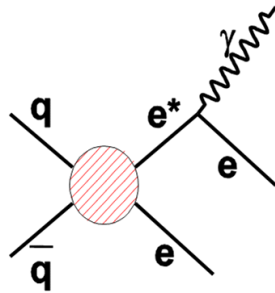
- Search for the production of **excited** or **exotic** electrons (e^*) in the following reaction:

$$p + \bar{p} \rightarrow e^* + e \rightarrow e\gamma + e$$
- This is a signature-based search for an $ee\gamma$ final state with a resonance in the $e\gamma$ channel; select two high p_T electrons + one photon ($E_T > 25$ GeV)
- **0 event observed**, set the **first mass limit on the e^*** for contact interaction model. For $M_{e^*} = \Lambda$, the mass limit is **785 GeV**

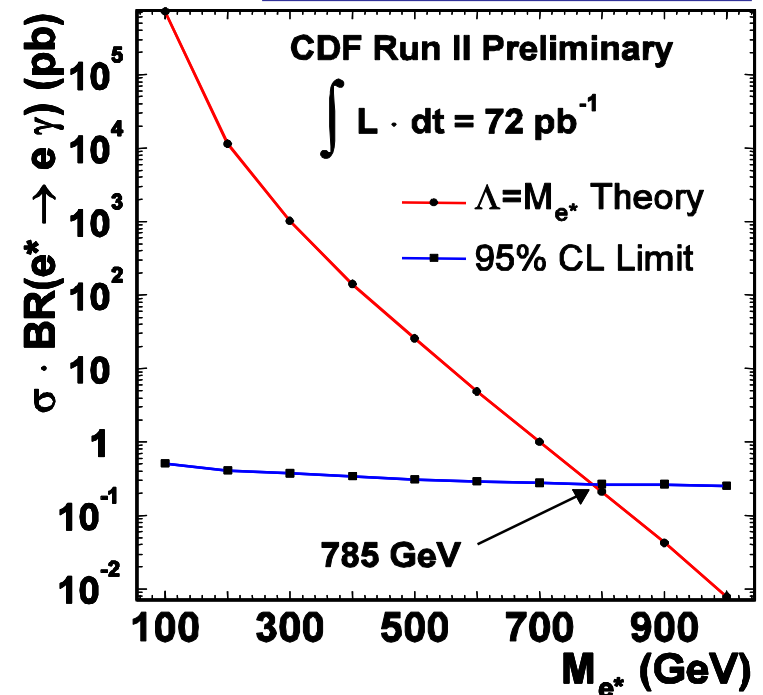
Λ = Compositeness Scale



Since cross-section depends on M_{e^*} & Λ , we obtain exclusion region using various values of M_{e^*} and Λ



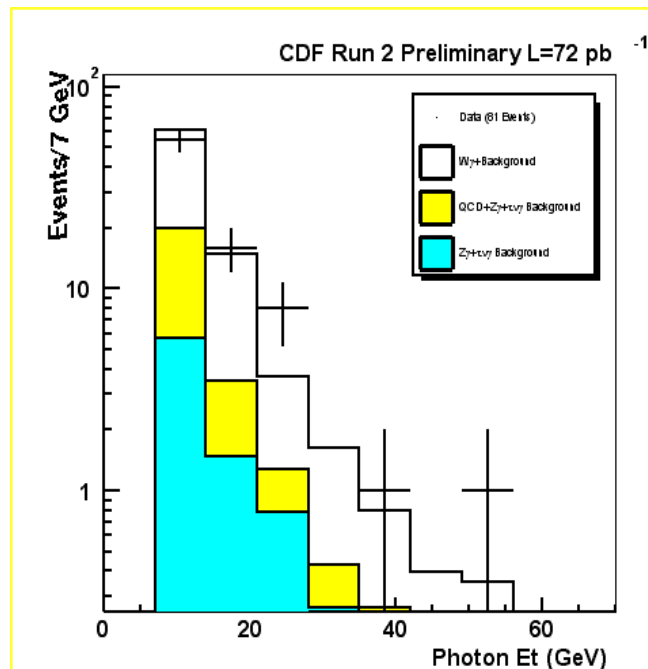
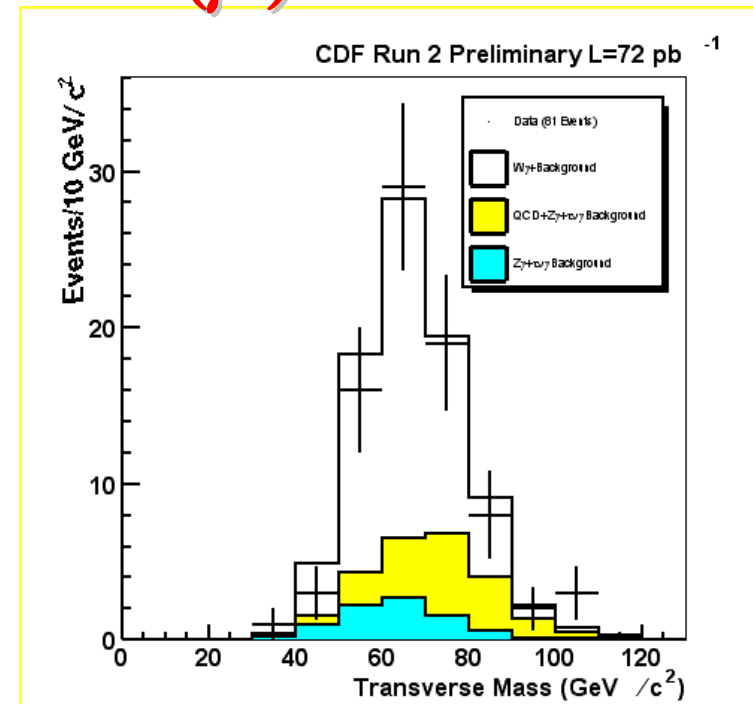
$M(e^*) < 785 \text{ GeV}$



$W\gamma$ Production with $W \rightarrow e(\mu) \nu$ at CDF

- **Physics:** look for evidence of anomalous coupling (New Physics)
- **Signature:** one high p_T lepton(e/μ) + γ with MET(>25), $(\Delta R(\gamma-l))>0.7$

- **Results:** No excess was found
Data: 43(38)
Signal MC+Background : $46.6 \pm 1.3 \pm 4.5$
 $(36.5 \pm 0.7 \pm 3.0)$



... derived the cross section for $\text{Et}(\gamma) > 7$, $\Delta R > 0.7$

Results consistent with SM

SM: $\sigma \cdot B(W_\gamma \rightarrow l\nu\gamma) = 18.7 \pm 1.3 \text{ pb}$

	Data	BGD	$\sigma \cdot B(W \gamma \rightarrow l \nu \gamma)$ (pb)
e	43	33%	$17.2 \pm 3.8_{\text{stat}} \pm 2.8_{\text{sys}} \pm 1.0_{\text{lum}}$
μ	38	29%	$19.8 \pm 4.5_{\text{stat}} \pm 2.4_{\text{sys}} \pm 1.2_{\text{lum}}$

SUSY 2003, Arizona

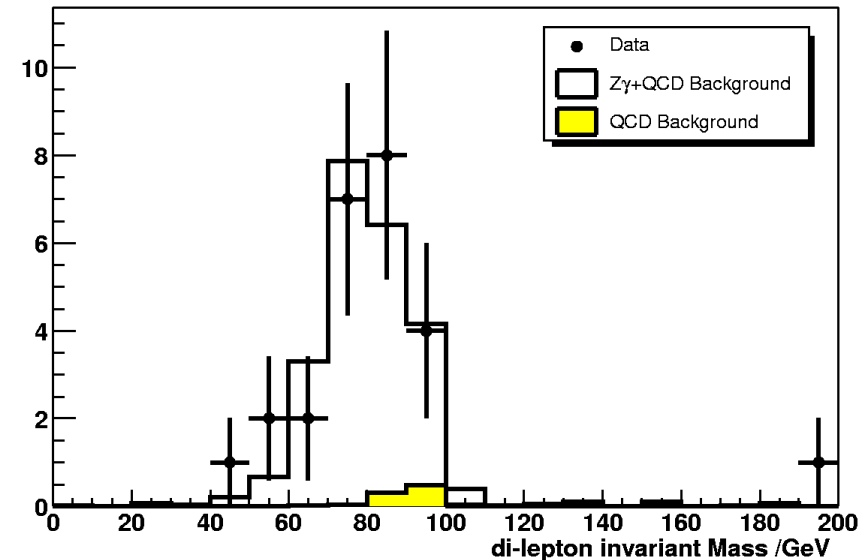
$Z\gamma$ Production with $Z \rightarrow ee(\mu\mu)$ at CDF

- **Physics:** look for evidence of anomalous coupling (New Physics)

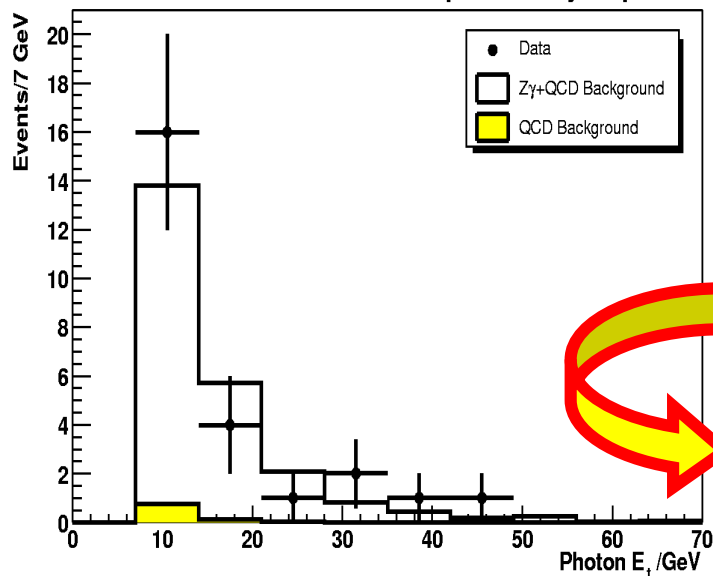
- **Signature:** two high p_T lepton(e/μ) + γ
($\Delta R(\gamma-l) > 0.7$)

- **Results:** No excess was found
Data: 11(14)
Signal MC+BGD : $10.8 \pm 0.9 \pm 0.6$
($12.4 \pm 1.2 \pm 0.7$)

CDF preliminary 72 pb⁻¹



CDF preliminary 72 pb⁻¹



X-section
for $E_t(\gamma) > 7$,
 $\Delta R > 0.7$

Results consistent with SM

SM: $\sigma \cdot B(Z\gamma \rightarrow ll\gamma) = 5.4 \pm 0.4$ pb

	Data	BGD	$\sigma \cdot B(Z\gamma \rightarrow ll\gamma)$ (pb)
e	11	4.6%	$5.5 \pm 1.7_{\text{stat}} \pm 0.6_{\text{sys}} \pm 0.3_{\text{lum}}$
μ	14	4.0%	$6.0 \pm 1.6_{\text{stat}} \pm 0.7_{\text{sys}} \pm 0.4_{\text{lum}}$

$W\gamma/Z\gamma$ data are in good agreement w/ SM



Conclusions

- ❑ Since photon is a clean and well measured EM object, **new physics searches with photons** are particularly interesting.
- ❑ CDF II is taking data actively since 2001 and larger samples are being collected/tested for new physics searches based on photon signature.
- ❑ It is producing its first results on new particle searches with photons. Two different approaches for new physics searches are in progress in CDF.
 - Signature based searches
 - Model based searches
- ❑ High luminosity photon data will **provide...**
 - the best opportunity for new physics discoveries, and will give any useful informations to theorists. (→ **Signature-based searches**)
 - experimental guidance to a better theoretical modeling of new physics production with photon in the final states (→ **Model-based searches**)



Backup Slides



Run I - Lepton+Photon Searches

- CDF has performed a model independent search in Run I for new physics that gives leptons, photons, missing E_T in final state
- Inspired by $ee\gamma\gamma + \cancel{E}_T$ candidate event

The SM prediction yields the observed rate of a lepton+photon (+Missing E_T) with 0.7% probability (~ 2.7 standard deviation for Gaussian distribution)

- Search Selection:
 $l(e/\mu)\gamma$ events ($E_T > 25$ GeV)
- Main backgrounds:
 $W/Z + \gamma$, lepton+fake γ

Category	Predicted μ_{SM}	Observed N_0	$P(N > N_0 \mu_{SM})\%$
All l, γ, X	—	77	—
Z - like e, γ	—	17	—
Two - Body l, γ, X	24.9 ± 2.4	33	9.3
Multi - Body l, γ, X	20.2 ± 1.7	27	10.0
Multi - Body l, l, γ, X	5.8 ± 0.6	5	61.0
Multi - Body l, γ, γ, X	0.02 ± 0.02	1	1.5
Multi - Body l, γ, MET, X	7.6 ± 0.7	16	0.7

It's an interesting result, but it's not a compelling observation of new physics!!
Run II analysis is in progress now

Recent theoretical explanation of the $\mu\gamma$ events is...

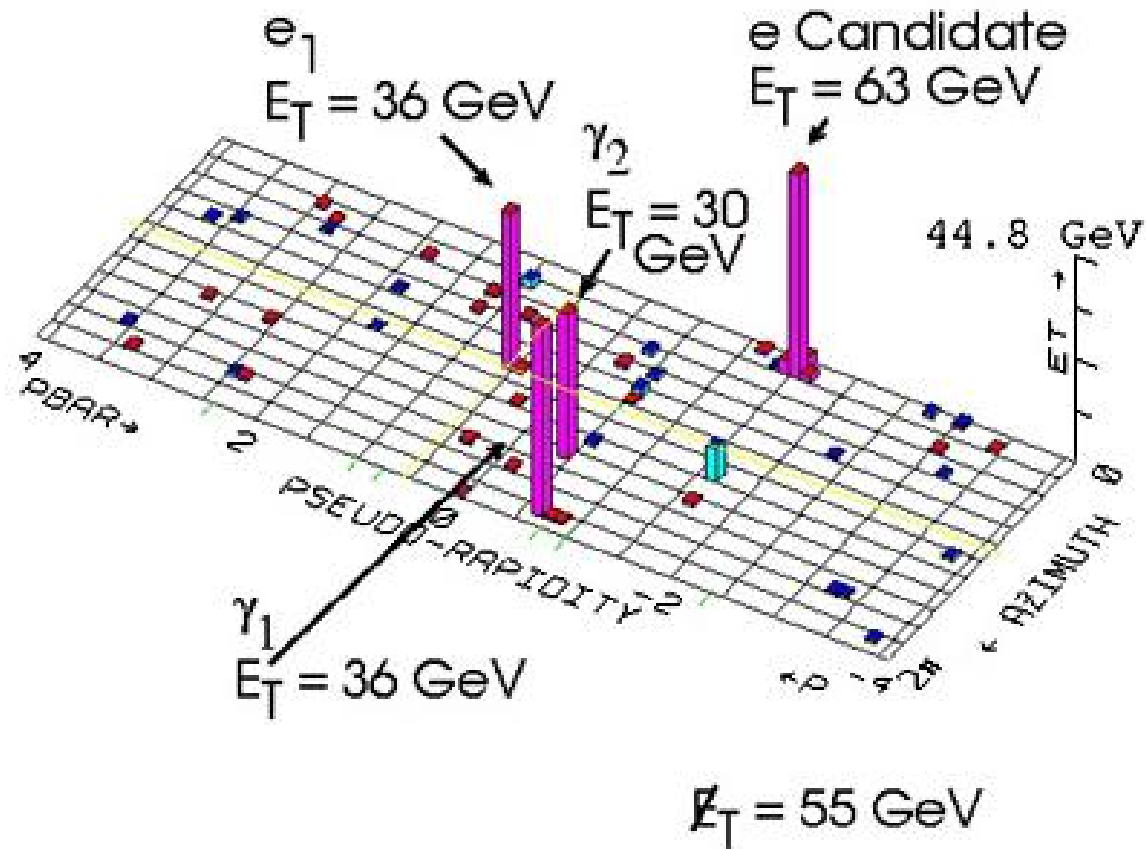
"Resonant smuon production with a single dominant R-parity violating coupling" (hep-ph/0111014)



CDF I Photon-based New Physics Searches

- **Search for Diphoton and \cancel{E}_T**
→ Gauge-Mediated SUSY Breaking ($\chi\chi$ in $\gamma\gamma + \cancel{E}_T + X$)
- **Search for Narrow Diphoton Resonances**
→ Bosphilic Higgs Search
→ Sgoldstino Search
- **Search for Photon and B-jet**
→ MSSM ($\chi_2^0 \rightarrow \gamma\chi_1^0$ via \tilde{g}, \tilde{q})
→ Technicolor ($\omega_T \rightarrow \gamma\pi_T \rightarrow \gamma b\bar{b} \rightarrow \gamma + 2 \text{ } b\text{-jets}$)
- **Search for Photon and Lepton**
→ $e\gamma + \cancel{E}_T, \mu\gamma + \cancel{E}_T, e/\mu\gamma + \cancel{E}_T$
- **Search for LED with Diphotons**
→ S-channel production of KK tower of Gravitations
- **Search for Photon and \cancel{E}_T**





**Run II has started, searches
are in progress**

